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A CONCEPTUAL MODEL ON HEAT TRANSFER EFFICIENCY IN THE DESIGN OF A SOLAR COOKER FOR DEVELOPING COMMUNITIES

G. FRY[1], L. SHOEN[2], P. B. SOB[3] & J. OOMMEN[4]

Department of Engineering, School of Natural and Social Sciences, Mount Vernon Nazarene University, 800 Martinsburg Road, Mount Vernon, USA

ABSTRACT

A detailed conceptual study has been carried out to investigate the characteristics of a solar cooker to maximize the solar energy exchange efficiency. Emphasis was placed on the long-term sustainability of the solar cooker for developing/rural populations, minimizing manufacturing costs while retaining structural strength, and ease of use for the operator. Using a solar cooker as a means for cooking food is an eco-friendly alternative compared to conventional methods (kerosene, wood, petroleum gas, or electricity), therefore, allowing a healthy avenue of growth for rural communities. However, many commercially available solar cookers are impractical, either due to large, bulky designs, or excessive cooking times. By modeling and optimizing the core mechanism of heat transfer and the physical properties of typical solar cookers, a more practical and efficient product can be constructed. Furthermore, multiple variations of solar cookers exist (i.e., box & reflectors) and the drawbacks and advantages of each model will be analyzed. In this investigation, the tools of stochastic mechanics, lognormal distribution, and mechanism of heat transfer were used to model and optimize the design performance of a solar cooker. The derived models were simulated using MATLAB and theoretical validation was performed using the engineering equation solver software. It was shown that the final optimization factor that was improved upon was the geometry of the absorption plate. Initial calculations indicate an overall system performance increase of 1.2% with the removal of the pot as shown in the findings. The proposed system demonstrated a general enhancement in all indicators of thermal performance when compared to a standard solar box cooker.

KEYWORDS: Solar Energy, Solar Cookers, Thermal Performance, Heat Transfer & Design

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Original Article

1.0 INTRODUCTION

As the world's population grows, the need for resources also grows exponentially. Consequently, the swelling demand for commodities such as wood often leads to massive deforestation in developing countries. The wood stripped from these areas is then exported to other nations, leaving the community with an acute scarcity of local resources. For the neighboring impacted areas, wood is an invaluable resource that is required for day-to-day activities, including the process of cooking food. Deforestation compromises the developing area's possibility for sustainable development. Therefore, locating an alternative energy source is of paramount importance for the continuation of the community, while the root issue of exploitation of the area's resources is solved. Solar energy is a freely available and non-polluting form of energy that can be utilized in a multitude of processes. Solar energy provides a clean and sustainable way of cooking food without the negative side effects of traditional methods (consuming local resources, polluting the environment with reactants, destroying ecosystems through harvesting of wood, etc.) (Aadiwal et al., 2017). Solar cookers can serve as multi-purpose devices: One, in serving as a safe way to cook food, and two as a tool to purify contaminated water through the process of boiling and collecting. Safe drinking water is often another struggle that these developing communities face, hence, access to a device that can solve several problems at once is appealing. Regions with tropical/desert climates receive direct sunlight the majority of the year, so the users can utilize the solar cooker to its maximum capabilities (Hain, 2021). When evaluating maximum efficiencies of each type of solar cooker, it is

assumed that direct sunlight is available under no cloud cover. Although, the amount of sunlight needed to function will be considered, as it is directly related to the success of the implementation of these devices. Furthermore, most non-negligible sources of heat transfer were investigated to conclude the overall heat transfer efficiency of the system. The most efficient model then was scrutinized to modify its components to maximize desired traits.

2.0 PRINCIPLES AND VARIATIONS OF SOLAR COOKERS

The foremost principle of solar cooking is that rays of sunlight strike a reflective surface and are concentrated into a primary cooking area. The reflected, more potent solar energy is then trapped and absorbed by the cooking container. The color and material of the container determine the effectiveness of the conversion of solar energy into heat (conduction). A black container will absorb nearly all solar energy that strikes it, while a white container will reflect it. Furthermore, the thermal conductivity of the container's material will hasten the cooking process. Finally, isolating the cooking container from outside factors, such as wind/ambient temperature will prevent convection heat loss.

2.1 Indicators of Solar Cooker Performance

During the comparison of solar cookers, relevant indicators of thermal performance should be considered for proper evaluation and optimization. The first indicator of performance is defined as the ratio of optical performance (η_o) and the overall heat loss coefficient of the system (U_L), defined by (Mullick et al., 1987) as,

$$F_1 = \frac{\eta_0}{U_L} \tag{1}$$

Generally, a low heat loss factor and high optical efficiency are preferable for solar cooker design. Accepted values for the first indicator should exceed or equal to 0.12. The second indicator for thermal performance involves testing the cooker under full load conditions, which is expressed by the equation given in (Mullick at al., 1987), as follows:

$$F_2 = \frac{F_1(MC)_w}{A\tau} ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-T_a}{H}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-T_a}{H}\right)}\right] \tag{2}$$

where F_1 is the first indicator, M is the mass of water (kg), C is the specific heat capacity of water (J/kg°C), A is the aperture area (m^2), τ is the time difference between T_{W1} and T_{W2} (s), T_{W1} is the initial water temperature (°C), T_{W2} is the final water temperature (°C), H is the average solar radiation incident on the aperture of the cooker (W/m^2), and T_a is the ambient temperature (°C). Finally, the cooking power (P) is defined by ASAE (American Society of Agricultural Engineers) as follows (ASAE, 2013),

$$P = (T_{w2} - T_{w1})\frac{MC}{600} \tag{3}$$

2.2 Variations of Solar Cookers

Three categories of solar cookers as shown in Figure 1 are commonly implemented in developing communities, namely, solar panel cookers, reflector/parabolic cookers, and solar box cookers.

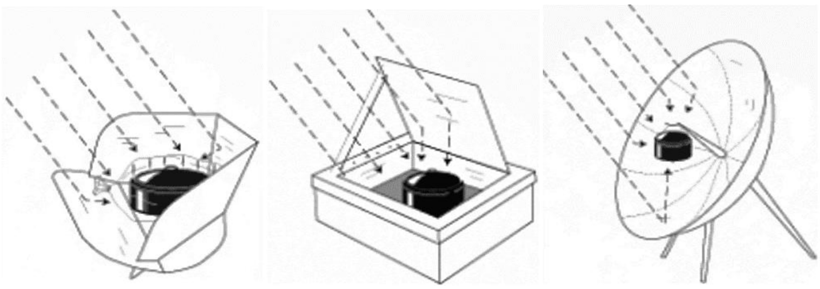


Figure 1: Types of Solar Cookers: (a) Solar Box Cooker; (b) Reflector Solar Cooker; and (c) Panel Solar Cooker [10].

Solar box cookers: Solar box cookers are the most common and commercially available type of solar cooker. Solar boxes utilize a highly reflective surface held at a specific angle (≅110° from horizontal) above the cooking area. The light reflected from this surface passes through a glass, or glass-like, material into an enclosed cooking area. Inside the cooking area is typically painted black to retain heat efficiently. The outer walls of solar boxes are typically a carbon fiber composite, minimizing weight, while maintaining structural strength and stiffness. Between the outer wall and inside the cooking area is insulation, such as glass wool combined with a wooden wall. A polyurethane foam seals the solar boxes joints, a heat-retentive solution of bonding. Solar box cookers mainly rely on convection and conduction for modes of heat transfer and can reach temperatures of 150°C.

Reflector solar cookers: Reflector solar cookers utilize a large parabolic reflective surface to focus light onto the cooking area. Unlike solar box and solar panel cookers, a reflector does not require a contained cooking vessel; the cooking container is exposed to the open air. Reflector solar panels use energy from the concentrated solar radiation to heat the bottom of the cooker placed at the foci of the parabola. Reflectors can often reach much higher temperatures than the other variations of cookers (350°C) and in a much shorter time frame (ASAE, 2013).

Panel solar cookers: Solar panel cookers are similar to box cookers, but with a few distinct differences. A panel cooker employs a contained cooking area to trap heat inside, allowing for convection to take place. Panel solar cookers implement 3-4 reflective surfaces that surround the cooking area. The panel solar cooker has the simplest design but retains heat poorly. A panel solar cooker can reach temperatures of approximately 200°C in optimal conditions (clear sky and low wind speed).

2.3 Selection of Solar Cooker Variation for Further Optimization

Each solar cooker model possesses characteristics that are desirable depending on the application that is sought. In order to move forward into the optimization phase, the most suitable model must be selected for heat transfer efficiency. It must be noted that heat transfer efficiency is not the sole factor that influences the most ideal model for a developing community. Day-to-day practicality, capability under a range of weather conditions, cooking time, and cost must be considered with the utmost importance. Shortcomings in any of the listed categories will lead to ineffective development. Table 1 demonstrates the advantages and disadvantages of each solar cooker variation. After deliberation of the optimal cooker for developing communities, the solar box cooker was selected for its well-rounded traits compared to the other variations. The solar box cooker has the lowest overall temperature of all the models, thus having the longest cooking times. However, the efficiency of radiation transfer to heat and the retention of that heat out-performs every model (Akoy et al., 2015). Furthermore, the solar box cooker is simple to operate and requires little intervention on the user's part. The solar box cooker can also operate in windy conditions, while the other models struggle due to their large reflective surface area. Also, solar box cookers are relatively inexpensive and simple to construct compared to other solar cooker variations (Kimambo, 2007). Finally, a thermal efficiency analysis between the differing solar cooker models was conducted by (Akoy et al., 2015), yielding the results found in Table 2. These results aided in the selection of a solar cooker model for heat transfer efficiency, as it provided experimental data to support our conclusion.

Table 1: Advantages and Disadvantages of Different Variations of Solar Cooker Models

Cooker Variation	Advantages	Disadvantages
Reflector Cooker	Reaches highest temperatures Fast cooking time	Unsuitable for windy conditions Expensive, difficult to manufacture, and bulky Needs to be adjusted continuously by user Low thermal efficiency
Panel Cooker	Reaches higher temperatures than box cooker Does not need to be adjusted Relatively high thermal efficiency	Excessive heat loss, relies on reflected radiation Subpar performance in cloudy conditions Heavier, more cumbersome than box cooker

Box Cooker	Light, inexpensive, simple construction Highest thermal efficiency Uses convection and conduction for cooking Suitable for windy and cloudy conditions	Suffers from low temperatures Leaks in seals of box cause poor performance Long cooking times

Table 2: Calculated Results of Constructed Solar Cooker Efficiency [5]

Solar cooker	Efficiency (%)
Parabolic	31.53
Box-type	77.4
Panel-type	67.4

2.4 Model Design Objectives

The current design is aimed at optimizing the two indicators of thermal performance listed in equations (1) and (2), minimizing heat loss through boundary materials, increasing heat transfer efficiency through dimensional alterations, and intensifying overall cooking power following equation (3). The model parameters that were enhanced are as follows: the absorption plate material and shape will be altered to diminish heat loss due to reflected light, the geometry of the cooking area will be analyzed to reduce the volume of air in the cooking area while maintaining adequate surface area, and a laminar composite containing wall will be created to trap heat effectively. These objectives were achieved through empirical modeling and simulation of the relevant identified model's parameters that impact the efficiency of the design.

3.0 METHODOLOGY

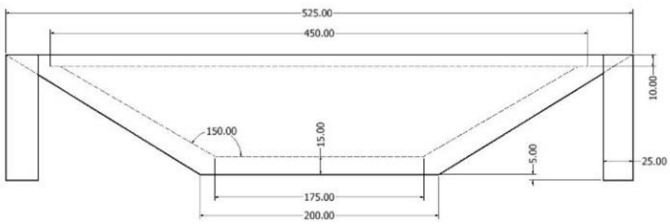


Figure 2: Absorption Plate Geometry (mm).

The conceptual model for a box solar cooker will be modeled to conform to ASAE standards. All property values, including thermal coefficients, convection heat transfer rates, and absorption / emissivity, etc. will be listed per manufacturer specifications. Ambient temperatures will be tested within the range of 20 - 35℃ per ASAE guidelines and testing conditions.

3.1 Mathematical Model

Considering the dimensions of the Absorption plate (Figure. 2) geometry as,

Absorption Plate Thickness = 0.00229m

Total Surface Area of Plate (A) = 0.2127 m^2

Thermal Conductivity (k) of: 6061 T6 Aluminum = 167 W/mK at 25℃ [8].

Pine Plywood = 0.13 W/mK

PINK Next Gen™ Fiberglas™ = 0.0360 W/mK (Pink Next Gen, 2022)

Pyrogel XTE = 0.023 W/mK at 100℃. [10]

Volume of air contained in frustum = 0.0174 m^3

Aperture Area = 0.2025 m^2

Standard Solar Radiation ASAE = 700 W/m^2

Absorptivity of: Black paint 0.98, Mirror 0.01

Convection heat transfer for steady ambient air (h_1): 10 W/m^2K, 14 W/m^2K trapped air (h_2)

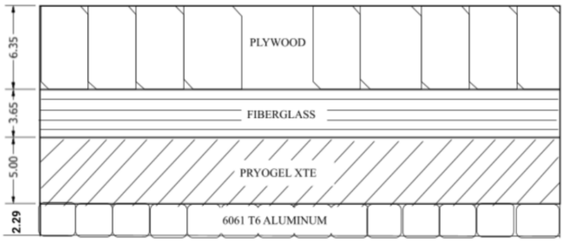


Figure 3: Laminated Composite Containing Wall (mm).

The dimensions and materials of the 15mm thick laminated composite containing wall can be seen in Fig.3. The thermal resistance network for heat transfer through the four layered composite wall subject to convection on both sides is given as:

$$R_{total} = R_{conv,1} + R_{ply} + R_{fiber} + R_{xte} + R_{alum} + R_{conv,2}$$

$$= \frac{1}{h_1 A} + \frac{L_{ply}}{k_1 A} + \frac{L_{fiber}}{k_2 A} + \frac{L_{xte}}{k_3 A} + \frac{L_{alum}}{k_4 A} + \frac{1}{h_2 A} \quad (4)$$

Equation (4) represents total resistance offered to the convection heat transfer or contained/surrounding air, and conduction resistance of the composite wall, where A is the total surface area of the absorption plate, L values represent the thickness of each respective layer, k values represent the thermal conductivity of each material, and h values are the convection heat transfer coefficient. The conceptual shape of the absorption plate can be justified with two hypothesized benefits, one, the frustum shape reduces the overall volume of air inside the cooking area, and two, the geometry allows for water to be directly placed on the plate, thus decreasing heat loss by removing the cooking pot. The bottom portion of the absorption plate would be unpainted to avoid water contamination from paint particles.

3.2 Thermal Performance Test

Thermal performance of the system will be analyzed according to the indicators listed above in equations (1-3). The amount of water is known and steady, and the ambient temperature is tested according to ASAE standards. Using MATLAB and Simulink software, a heat source will be applied to the absorption plate and analyzed graphically. The overall heat loss of the system will be partially idealized, where efficiencies of components are based on hypothesized values.

4.0 RESULTS AND DISCUSSION

Employing the given values of thermal properties listed in methodology, the indicators on thermal performance were calculated for our theoretical model, which can be seen in Figure.4.

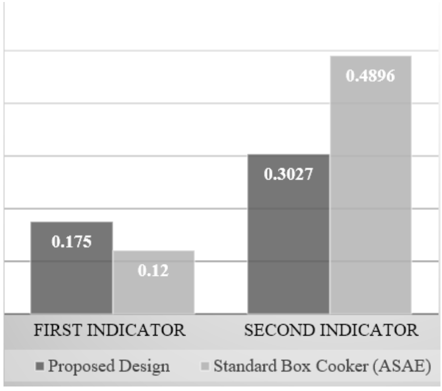


Figure 4: Comparison of Indicators of Thermal Performance.

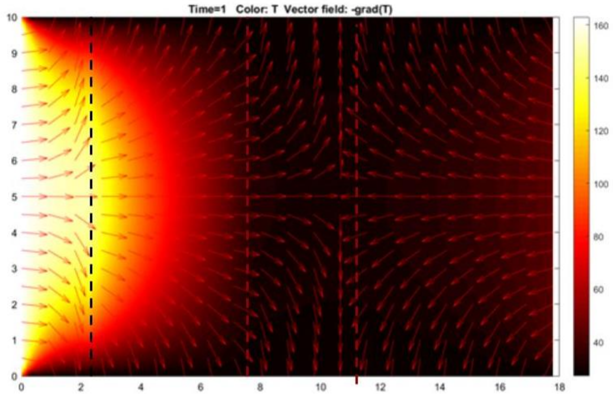


Figure 5: Heat Flow Diagram with Indicated Temp ˚C.

In this graph, the proposed model was compared against the standard box shape solar cooker. Several factors of the proposed design theoretically increased overall thermal performance. Firstly, the decreased overall volume of air contained within the system prevented unnecessary heat loss. The proposed model contains 49% less m^3 of air within the system. Secondly, the addition of the laminated composite wall significantly minimized heat loss through conduction between the plate and outer wood walls. Fig.5 illustrates the heat flow direction and temperature at the given layers. This figure was created using MATLAB's Partial Differential Equation Modeler characterized for heat transfer. Each layer was assigned values according to their respective thermal traits, and an appropriate thermal load was assigned to the left most boundary. Furthermore, a slight heat flux was assigned to the right most boundary (plywood wall) to attempt to account for diffuse radiation that strikes the wood. The model used approximately 14,000 mesh nodes during the process, where the nodes were primarily concentrated on the contacting points of the layers. The model yielded a maximum plate temperature of 163˚C at quasi-static equilibrium. Further, the maximum internal air temperature reached 143˚C. As shown in Fig.5, the majority of the heat flow was absorbed by the Pyrogel XTE layer, while the remainder was absorbed by the fiberglass layer.

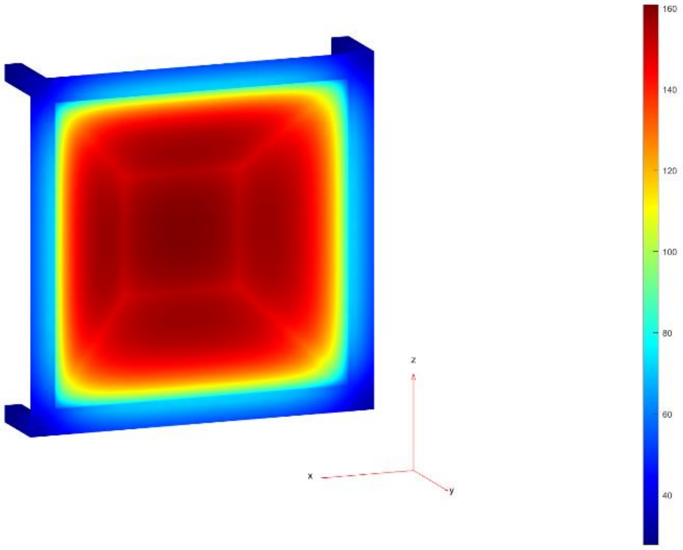


Figure 6: Temperature Distribution in Absorption Plate System ˚C.

The fiberglass layer reached an average temperature of 63˚C. The next optimization factor that was improved upon was the heat loss through ground conduction. The support legs of the solar cooker protrude slightly further than the lowest point of the absorption plate, therefore creating an air layer between the ground and containing wall. In many cases, the ground is colder than the ambient air, or rather has a higher heat capacity. Therefore, the cold dirt draws heat from the solar cooker, decreasing overall performance. The final optimization factor that was improved upon was the geometry of the absorption plate. If the intention of the user were to boil water, the geometry of the plate allows for the plate to be used as a bowl, so a pot would not be needed. A square lid would simply be placed over the water, allowing for an increase in performance due to the removal of heating the pot. Initial calculations indicate an overall system performance increase of 1.2% with the removal of the pot. Of course, a pot may still be used if necessary and the system will still function efficiently. Fig.6. shows the encompassing temperature distribution throughout the absorption plate system.

4.1 Indicators of Thermal Performance

The proposed system demonstrated a general enhancement in all indicators of thermal performance. Regarding the first indication of thermal performance (1), the model exceeded the minimum requirement of 0.12 imposed by ASAE guidelines. The model had a calculated F_1 of 0.175, which can be attributed to the optimizations made in reduction of heat loss. A higher value of F_1 denotes a more efficient system, with respect to optical efficiency and heat loss coefficient of the system. Furthermore, the second indicator was significantly improved upon when compared to a standard ASAE box cooker. In this case, a low value of F_2 is more desirable. The value of F_1 influences the calculated value of this indicator, therefore optimization of F_1 should be conducted prior to analysis of F_2. The main method through which F_2 was optimized was by reduction of τ in equation 2. A higher plate temperature, removal of the cooking pot, and reduction of heat loss through conduction all contribute to the overall heating time of the water in the system. Therefore, the optimizations made in these categories will drastically affect F_2. Finally, the cooking power for an 11˚C temperature difference across a ten-minute interval for 1kg of water was determined to be 76W.

4.2 Tentative Final Model Proposal

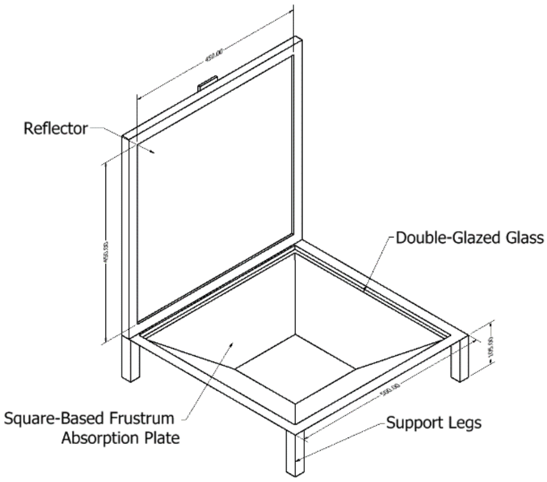


Figure 7: Final Model Proposal Schematic ˚.

The final proposed model including the mirror, double-glazed glass, and support legs can be seen in Fig.7. The reflector mirror has dimensions that match the aperture of the absorption plate. Furthermore, the mirror assembly is supported with a notched hinge support, which can be adjusted to change the declination. The notched support will securely hold the mirror in place, while being able to be lifted out of place with ease when needed. Due to the unstable nature of the square based frustrum design, support legs are required to stand during windy conditions.

4.3 Theoretical Validation of the Proposed Solar Cooker Design using View Factor Relations for the 3-D Geometry

To validate the proposed design in Figure. 7, equations (1) to (4) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) as seen in Figures 8a and 8b while employing the parameters and data shown in proposed plate geometry in Figure. 2.

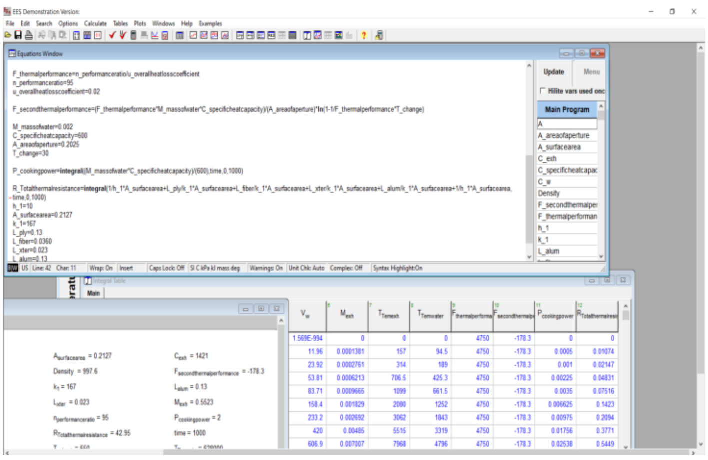
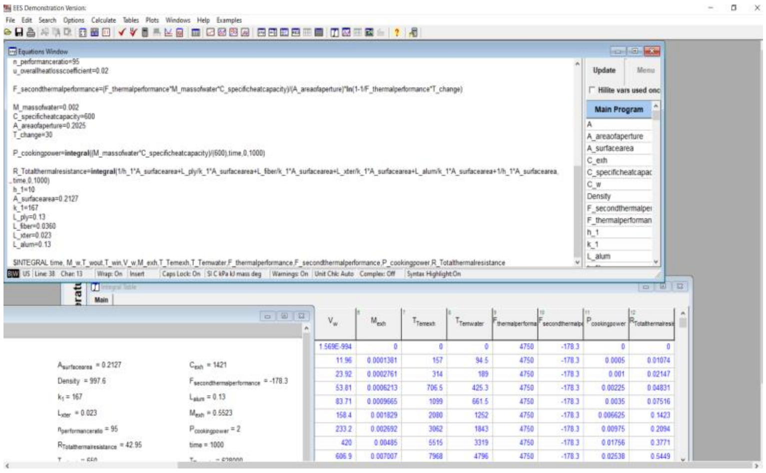


Figure 8(a): Engineering Equation Solver Software (F-Chart Software, Madison, W153744, USA) Simulation.



8 (b)

Figure 8 (b): Engineering Equation Solver Software (F-Chart Software, Madison, W153744, USA) Simulation.

The simulation was done by taking into consideration the different variation of the critical parameters that impact performance, time, cooking power, and thermal resistance of the proposed model as shown in Figure. 7. The following obtained results are shown in Figure.9 (a-b).

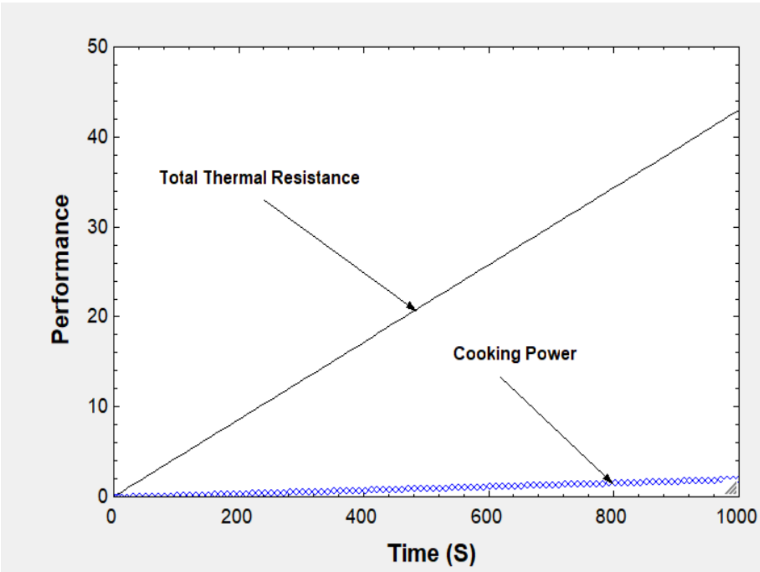
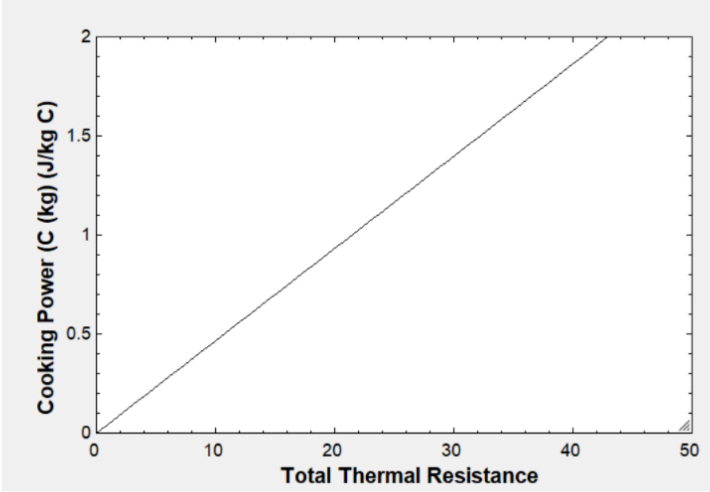


Figure 9(a): Performance Evolutions of Time for Cooking Power and Total Thermal Resistance.

It is observed from Figure. 9(a) that the nature of performance evolution of time increased more on the thermal cooking resistance when compared with the cooking power in the current design of solar cooker.



(b)

Figure 9(b): Cooking Power Evolution of Total Thermal Resistance.

It is also observed as shown in Figure 9(b) that as the design cooking power increased, the total thermal resistance also increased. This is because conduction and convection of heat transfer occurred simultaneously during radiation process of the designed solar cooker. The change of performance and cooking power vary due to emissivity of the surface, absorptivity, reflectivity, transmissivity, geometry, and change in temperature which are critical properties that impact heat transfer by radiation and coefficient of heat transfer for convection and conduction. The current study is in line with view factor relations for the proposed model shown in Fig.7. Thus, the proposed study validates the theory and practice of radiation heat transfer.

5.0 CONCLUSIONS

The research project was aimed at improving the design efficiency of a solar cooker for developing communities. This was achieved through empirical modeling and simulation of the relevant identified model's parameters that impact the efficiency of the design. The experimental results show that indicators (F_1 & F_2) and cooking power satisfied ASAE Standards for thermal performance testing of a box type solar cooker. Furthermore, under no load conditions, the maximum absorption plate temperature reaches 163˚C. Utilizing the equation of overall thermal efficiency given in (El-Sebaii and Ibrahim, 2005), the performance is found to be 53% for a water load of 1kg. The design proposed is feasible for rural communities and will provide a non-polluting source of cooking.

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